Bidirectional Reflectance Factors of Agricultural Targets: A Comparison of Ground-, Aircraft-, and Satellite-Based Observations

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*T*he bidirectional reflectance factor (BRF) of most natural surfaces exhibits substantial departure from lambertian behavior, yet the magnitude of its effect in off-nadir imagery from the SPOT satellite remains mostly undocumented. Field investigations were conducted at the Maricopa Agricultural Center in Arizona to explore this phenomenon using three wavelength intervals (green, 0.50–0.59 μm; red, 0.61–0.68 μm; and NIR, 0.79–0.89 μm). During 1988 and 1989 observations spanned two consecutive days during which the SPOT radiometer viewing angles differed by 34°. Ground-based BRFs were obtained for nadir and off-nadir viewing angles over replicated transects in cultivated soil, cotton, and wheat fields using radiometers mounted on a backpack. Aircraft data were measured from flight lines about 150 m above ground level with a nadir-oriented radiometer. SPOT digital imagery was converted to ground equivalent BRFs using specific calibration factors for the sensor, estimates of exoterrestrial radiation, solar zenith angles, and measurements of atmospheric optical depths. Reflectance factors varied with sensor, target, wavelength interval, and viewing and illumination geometry. Ground data were a strong function of solar zenith angle, revealing systematic differences in BRF behavior of each cover type. Good agreement was found between ground- and aircraft-based observations collected with nadir-pointed radiometers. For each wavelength interval, linear regression yielded $R^2 > 0.99$ and regression slopes averaging 0.96. Ground and aircraft data also revealed negligible changes in day-to-day reflectance from cultivated soil, cotton, and wheat targets. However, large differences were observed in SPOT imagery acquired on consecutive days. As expected, correlations between nadir aircraft observations and off-nadir satellite data were relatively poor $(0.66 < R^2 < 0.80;$ slope $\approx 0.76)$ partially due to differences in sensor viewing angles. Off-nadir satellite and off-nadir ground data were better correlated $(0.91 < R^2 < 0.96;$ slope $\approx 0.83)$. However, satellite-based BRFs were nearly double the ground-based values at low levels of reflectance (visible bands over dense vegetation). Possible reasons for discrepancies between satellite and ground off-nadir measurements include systematic bias in surface reflectance measurements, inadequate atmospheric correction of satellite data, adjacency effect from nearby surfaces, and inaccurate satellite sensor calibration.

INTRODUCTION

The potential for using satellite imagery as an agricultural resource management tool was enhanced with the launch of SPOT-2 in February 1990. This is the second of two satellites having cross track pointing capabilities that allow frequent coverage of specific targets, albeit at different view angles. SPOT-1 and SPOT-2 are in sun synchronous orbits that cross directly over the same point on the equator once every 26 days, being offset from each other by 13 days. Both are equipped with two radiometers that can be pointed as much as 27° on either side of nadir. This pointability makes it feasible to acquire imagery of the same target up to 11 times (at midlatitudes) during the 26-day orbital cycle of each satellite. The possibility of obtaining as many as 22 acquisitions during a 26-day period is an attractive feature for natural and agricultural resource management purposes. The pointability benefits are, however, partially offset by the attendant problem of compensating for the differences in view angles. For quantitative comparison of a series of satellite acquisitions, it is necessary to account for atmospheric distortions and the anisotropic (i.e., bidirectional) reflectance properties of surface targets.

Most agricultural surfaces are conspicuously nonlambertian, having complex bidirectional reflectance distribution functions (BRDF), which result in reflectance factors being dependent upon sensor view angle (Kimes, 1983) and the distribution of irradiance from the sky (Kriebel, 1976). The complete BRDF for a surface is difficult to specify because all possible illumination and viewing geometries would need to be measured. As a result, it is usually approximated by measuring bidirectional reflectance factors (BRFs) for a limited set of illumination and viewing geometries. Although BRFs are often portrayed as being static for a given crop species, in reality they change dynamically as plants emerge from a bare soil field, develop into a fully vegetated canopy, reproduce, and then senesce prior to harvest. Kirchner et al. (1982) presented data that show this evolution for a developing alfalfa (*Medicago sativa* L.) canopy. Seasonal BRFs are also modulated by plant stress, canopy architecture, and additional factors that are not directly related to crop condition itself such as row orientation, wind at the canopy surface, heliotropic leaf movements, presence of dew on the leaves, etc. (Jackson et al., 1979; Lord et al., 1985; Schutt et al., 1985; Pinter, 1987). The BRF of agricultural targets has important consequences for the interpretation of data from the high resolution multispectral radiometers (HRV) on SPOT, as variations in observed reflectance due to changes in look angle and time of acquisition can occur from one day to the next even when crop conditions have not changed. The problem becomes even more recalcitrant when one considers the effect of changes in atmospheric path and adjacency effects for different view angles (Dave, 1980). Such factors add considerable complexity to the interpretation of sequential images.

Illumination and viewing geometry effects on bidirectional reflectance have been demonstrated using aircraft multispectral scanner data (e.g., Salomonson and Marlatt, 1968; 1971; Ott et al., 1984) and with ground-based instruments (e.g., Pinter et al., 1983; 1987; Kimes et al., 1984; Shibayama and Wiegand, 1985; Deering and Leone, 1986; Deering et al., 1989). Some reports appear to conflict on the relative importance of the atmosphere and nonlambertian surface properties. Ott et al. (1984), for example, concluded that the atmosphere was important, but most of the view angle dependency in wide angle aircraft scanner data resulted from surface anisotropy. However, a recent modeling effort by Pinker and Stowe (1990) raises questions about the need to account for surface BRFs when interpreting data at satellite scales. They simulated BRF at the top of the atmosphere using the radiative transfer model of Braslau and Dave (1973) and assuming lambertian behavior of light reflected from surface targets. Their simulation compared favorably with observations from NIMBUS-7, implying that the atmosphere was responsible for most of the anisotropy seen in low resolution satellite imagery.

In addition to surface anisotropy and atmospheric effects, sensor calibration is important in obtaining accurate bidirectional reflectance factors using satellite data. The fact that preflight calibrations may not strictly apply in a space environment, and degradation of sensors occurs with age, make inflight calibration techniques essential (Slater et al., 1987). Such calibrations are generally made over bright targets because unfavorable

Table 1. Target Characteristics for Field Sites Measured at the Maricopa Agricultural Center on Overpass Dates[a]

| Site | Surface Soil Texture[b] | Crop | Row Geometry | | Plant Characteristics | | |
			Direction	Spacing	Height (m)	LAI (m^2/m^2)	Biomass (g/m^2)
11 and 12 June 1988 Overpasses							
A	CL	cotton	N–S	1.0 m	0.31	0.42	58
B	SL	cotton	N–S	1.0 m	0.21	0.18	24
C	SCL	cotton	N–S	1.0 m	0.34	0.51	71
9 and 10 April 1989 Overpasses							
D	SL/SCL	wet wheat	E–W	0.16 m	0.97	4.86	1134
E	SL/SCL	dry wheat	E–W	0.16 m	0.96	3.87	1040
F	CL	furrowed soil	N–S	1.0 m	NA	NA	NA

[a] Green leaf area index (LAI) and dry biomass are given for plant canopies.

[b] Soils were classified as reclaimed Trix [fine-loamy, mixed (calcareous), hyperthermic Typic Torrifluvents]. Three surface soil textures occurred in these fields: clay loam (CL), sandy loam (SL) and sandy clay loam (SCL) (Post et al., 1988).

signal-to-noise ratios make calibration with dark targets (for instance, visible reflectance from dense vegetation) difficult.

The objective of this report is to compare reflectance factors obtained simultaneously from ground, aircraft, and satellite altitudes on consecutive days at different viewing geometries and sun angles. The measurements were made over agricultural targets that presented a diversity of surface conditions, and thus a wide range of surface reflectances.

MATERIALS AND METHODS

Experimental Site

Experiments were carried out at the University of Arizona's Maricopa Agricultural Center (MAC) located at 33.075°N latitude, 111.983°W longitude (approximately 40 km south of Phoenix, Arizona) at an elevation of 358 m. Measurements were obtained on 11 and 12 June 1988 and 9 and 10 April 1989 in four different fields, measuring approximately 1600 m (EW) by 270 m (NS). Additional details on cropping patterns, soil texture, and plant characteristics are presented in Table 1.

Reflectance Measurements

Reflectance factors at ground level were obtained by walking along specific transects in several fields

with two Exotech Model 100BX[1] radiometers suspended 1.6 m above the ground surface on a backpack apparatus. Sensors had 15° field-of-view (FOV) optics and spectral bandpass filters similar to the SPOT HRV radiometers (green, 0.50–0.59 μm; red, 0.61–0.68 μm; and NIR, 0.79–0.89 μm). The Exotechs were positioned to achieve a mostly coincident view of each target, enabling almost simultaneous observation from nadir and off-nadir angles (the latter corresponding to the HRV viewing direction of SPOT on each pair of days). Viewing angle assignments were rotated between the two radiometers to minimize bias that different instruments and positions might introduce into the data.

Measurements were made in a furrowed soil field, three cotton (*Gossypium hirsutum* L. var Deltapine 77) canopies with visually different biomass levels and two adjacent areas in a spring wheat (*Triticum durum* Desf. var Aldente) field. One of the wheat targets, here termed "wet," had been irrigated 7 days prior to the measurements and presumably had optimum water status; the second, "dry," had not been irrigated for 3 weeks but was showing minimal visual symptoms of stress at the time of the measurements. In the furrowed soil and cotton targets, measurements were made along five replicate, 6-m-long transects. In the

Table 2. Summary of Ground-, Aircraft- and Satellite-Based Data Sets Obtained at MAC for Targets in Table 1[a]

| Sensor | Date | Time | Sensor Incidence Angles | Solar Angles | |
				Zenith	Azimuth
Ground	11 Jun 88	0905 h	− 10°, 0°, + 23°	51.5–39.8	85–93
Exotechs		1059 h	− 10°, 0°, + 23°	26.7–17.9	104–119
		1208 h	− 10°, 0°, + 23°	12.7–10.0	139–173
	12 Jun 88	0817 h	− 10°, 0°, + 23°	61.0–50.5	80–86
		1005 h	− 10°, 0°, + 23°	37.7–28.4	94–102
		1140 h	0°, + 23°	18.2–11.5	118–147
	9 Apr 89	0919 h	− 23°, 0°, + 10°	54.8–45.9	105–114
		1106 h	− 23°, 0°, + 10°	34.8–28.6	130–148
		1224 h	− 23°, 0°, + 10°	25.9–25.1	164–176
	10 Apr 89	0828 h	− 23°, 0°, + 10°	64.8–55.6	97–104
		1028 h	− 23°, 0°, + 10°	40.6–33.6	120–132
		1145 h	− 23°, 0°, + 10°	28.9–25.1	145–169
Aircraft	11 Jun 88	1141 h	0°	14.3	131
Exotech	12 Jun 88	1110 h	0°	19.8	115
	9 Apr 89	1119 h	0°	29.9	143
	10 Apr 89	1104 h	0°	31.6	137
SPOT	11 Jun 88	1133 h	+ 23.4°	15.6	126
HRV-XS	12 Jun 88	1113 h	− 10.7°	19.1	116
	9 Apr 89	1125 h	+ 11.7°	29.2	146
	10 Apr 89	1106 h	− 22.3°	31.3	138

[a]All angles are in degrees.

wheat targets, three replicate, 20-m-long transects were measured. All transects were oriented parallel to the scan track direction of the SPOT radiometer (≈ 100° east of true north). Replicate transects were positioned in a diagonal that was a minimum of 60 m distance from the dirt roads bordering the fields and which spanned the middle part of each field. Twenty-four, evenly spaced measurements were taken along each transect (four measurements per row in soil and cotton targets). While collecting data, the operator first walked east along the transect with the radiometers suspended over the canopy toward the south. After completing measurements over all replicates, the operator returned along a reciprocal bearing (≈ 280°) having the radiometers suspended toward the north and using a different off-nadir viewing angle. A comparison of nadir reflectance factors obtained along opposite bearings revealed minimal bias caused by changes in illumination source–observer–target geometry. The size of the ground footprint for each 15° lens of a nadir-pointed, backpack-mounted Exotech was a circular area approximately 0.42 m in diameter. Footprint size decreased to 0.37 m and 0.17 m, respectively,

at the top of a 20 cm high cotton crop and a 97 cm wheat canopy.

Ground measurements were acquired over each target three times each day from early morning until after the satellite overpass time (Table 2). By convention, nadir viewing angles were represented by 0°; off-nadir viewing angles were assigned a positive value when the radiometer was looking toward the east and a negative value when pointed west.

Analog voltage signals from both Exotechs were recorded with time of day on a Polycorder data collection device. Irradiance in each wavelength interval was inferred from measurements over a horizontally positioned, painted $BaSO_4$ reference panel. These observations were taken before and after measurements at each field site with both radiometers pointed normal to the panel surface. Wavelength-dependent calibration factors were applied to compensate for the nonlambertian characteristics of the panel (Jackson et al., 1987). Reflectance was calculated as the ratio of the radiometer output over each target to the time-interpolated output over the $BaSO_4$ panel. Radiometers were tilted 5–10° toward the south when

solar zeniths were less than 20° to prevent self-shadowing on the reference panel.

Because targets were up to 0.5 km apart, travel time caused a 20–30 min interval between measurements and prevented the collection of all ground data simultaneously with either the aircraft or the satellite acquisitions. Thus ground-based data were interpolated for times of aircraft and satellite overpasses by using least squares polynomial curves that were statistically fit through the reflectance factor versus solar zenith angle data. Cotton canopy reflectance data obtained near solar noon at a viewing angle of −10.5° on 11 June 1988 and wheat data at −23° collected during the final set of measurements on 9 April 1989 were not included in regression analysis because the target areas were partially shaded by the radiometers.

Aircraft-based radiant exitance data were obtained using an Exotech radiometer configured with SPOT filters and 15° FOV optics. Flight times coincided within several minutes of satellite overpass times (Table 2). Measurements were obtained along a transect that bisected each field in its long axis using a nadir view and a nominal 150 m altitude. Pixel diameter at the surface was about 40 m. Simultaneous color video imagery was used to extract subsets of 6–10 aircraft pixels that overlapped ground transects. Reflectance factors were derived from irradiances estimated concurrently via a second Exotech positioned over another calibrated $BaSO_4$ reference panel (Moran et al., 1990, this issue). Additional details concerning the multispectral aircraft data set can be found in Daughtry et al. (1990, this issue).

SPOT overpass times differed by about 20 min and view angles differed by about 34° on consecutive days (Table 2). The same satellite radiometer (HRV-2) was employed on all four dates. Average digital numbers (DNs) were obtained for 9–25 adjacent pixels that encompassed sites measured using ground-based radiometers. DNs were converted to surface reflectance factor values following procedures similar to those used by Holm et al. (1989) for Landsat Thematic Mapper (TM) data. The justification for the specific approach used in these experiments was examined by Moran et al. (1990, this issue). Briefly, the conversion algorithm involved two steps: 1) Radiance at the satellite was computed from DN values using the

SPOT-1 HRV calibration coefficients and 2) surface reflectance was computed from radiance at the satellite using measurements of optical depth on the day of satellite overpass (Biggar et al., 1990, this issue) and a radiative transfer model (Herman and Browning, 1975). The correction procedure assumed cloud-free conditions and accounted for multiple scattering and absorption in the atmosphere and off-nadir sensor viewing.

RESULTS AND DISCUSSION

The extent to which a plant canopy modifies reflectance does not depend solely on intrinsic variables such as percentage cover, the density of its biomass, or the architectural arrangement of its component elements. Solar zenith and azimuth angles are important external factors which also affect measured reflectance. These illumination angles determine the primary path that incident light will trace into the canopy, influence the number of interactions that light will have with various canopy components, and ultimately control the relative proportions of soil and plant tissue that will be illuminated. Sensor viewing direction and field of view are also significant because most canopies are nonlambertian in behavior and individual components can display specular reflectance characteristics. In partial cover canopies, proportionately more plant material is "seen" with off-nadir viewing angles than with nadir views.

The Soil Target. The ground-based reflectance factors of the furrowed, bare soil field (Fig. 1) offer insight into the effect that changing solar illumination angles and viewing angles have on a relatively simple agricultural target without vegetation. In this example, cotton was planted several days earlier but had not yet emerged. Plant beds were oriented in a NS direction with the tops 0.2–0.3 m higher than the furrows. The surface texture of the soil in the beds and furrows was moderately coarse with individual soil aggregates smaller than 1.5 cm in diameter. Reflectance factors in visible and NIR wavelengths were inversely related to solar zenith angles and could be explained principally by the amount of shadows present on the surface. Small solar zenith angles near midday completely eliminated shading of furrows by the plant beds and
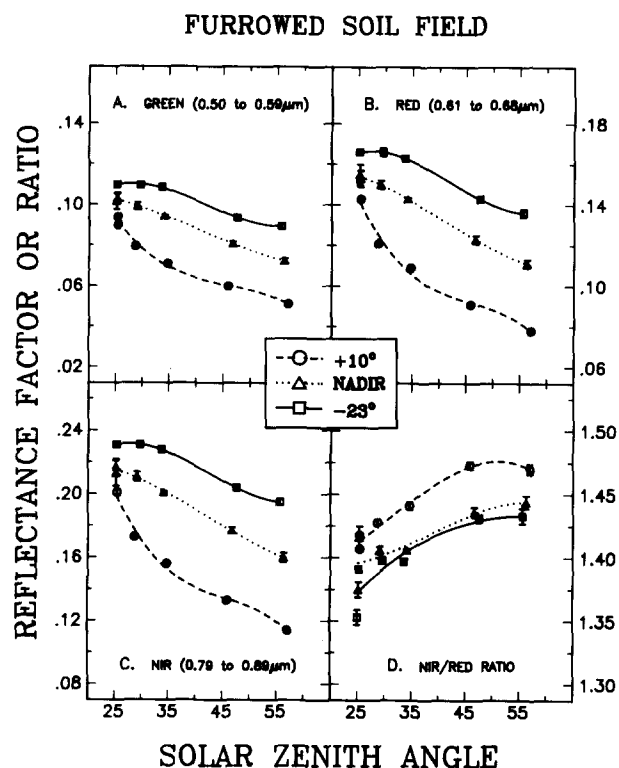
FURROWED SOIL FIELD

COTTON FIELD (NS ROWS)

Figure 1. Ground-based, BRF in SPOT HRV wavebands and NIR to red ratios measured on 9 and 10 April 1989 in a field having clay loam soil and north–south furrows. Each data point is an average of 120 (off-nadir) or 240 (nadir) measurements. Vertical bars indicate ±1 standard error from five 6-m-long transects. Lines represent best fit polynomial curves through data points for a given view angle.

Figure 2. Ground-based, BRF in SPOT HRV wavebands and NIR to red ratios measured on 11 and 12 June 1988 in partial cover cotton fields planted in north–south rows. Leaf area index (LAI) was 0.5 for Figure A)–C). Each data point is an average of 120 (off-nadir) or 240 (nadir) measurements. Vertical bars indicate ±1 standard error from five 6-m-long transects. Lines represent best fit polynomial curves through data points for a given view angle.

reduced microshading caused by the small clumps of soil on the surface. This increased the nadir reflectance factors to a maximum of 0.10, 0.15, and 0.22, for green, red, and NIR light, respectively, when the solar zenith was 25°. These values averaged 35–40% higher than those measured at 0830 h when the zenith was 57°.

Off-nadir reflectance factors responded to changing proportions of shaded and illuminated soil in an expected fashion. For any given solar zenith angle the lowest reflectance factors were observed when the sensor was tilted toward the "cold" spot of the target (+10°); highest when sensor viewed toward the hot spot (−23°). Reflectance factors from the different viewing directions converged as the solar azimuth angle approached 190°, a point where the azimuthal orientation of the two off-nadir viewing angles (100° and 280°) was perpendicular to the direction of incoming light. We speculate that off-nadir viewing directions would have an opposite associa-
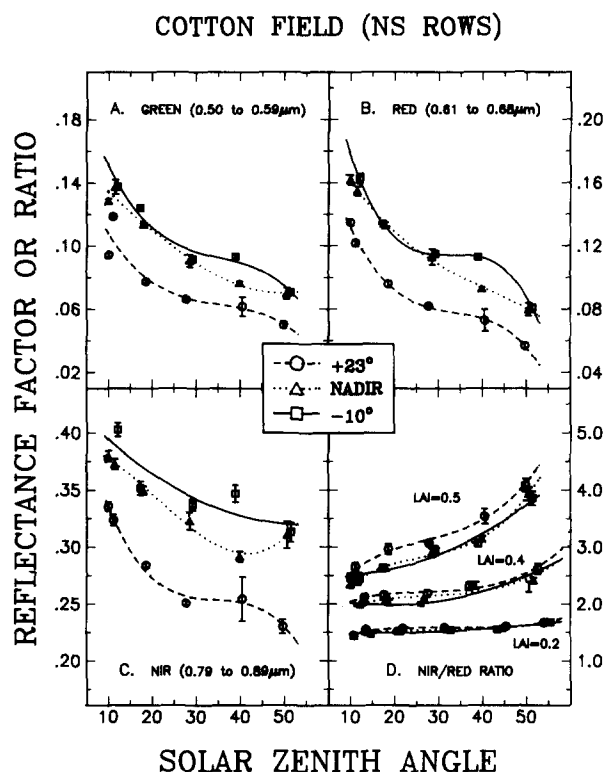
tion with the hot and cold spots in the target if the measurements had been repeated at a solar azimuth > 190°. Furthermore, if the plant beds had been oriented in an EW fashion, the slope of the relationships shown in Figure 1 would likely have been less steep (Jackson et al., 1979).

The ratio of NIR and Red reflectance factors for the furrowed soil target changed systematically with solar zenith and viewing angle [Fig. 1D)]. The change was relatively insignificant, however, when compared with the maximum NIR/red values occurring when plants were present [compare expanded scale of Fig. 1D) with Figs. 2D) and 3D)]. Thus, for an unvegetated target, ratioing suppressed the illumination and viewing angle induced changes because variation in the red was accompanied by a proportional change in the NIR.

The Cotton Targets. The cotton targets were more complex than the furrowed soil and serve to illustrate the effects of varying solar zenith and

HEADED WHEAT FIELD (LAI = 4.9)
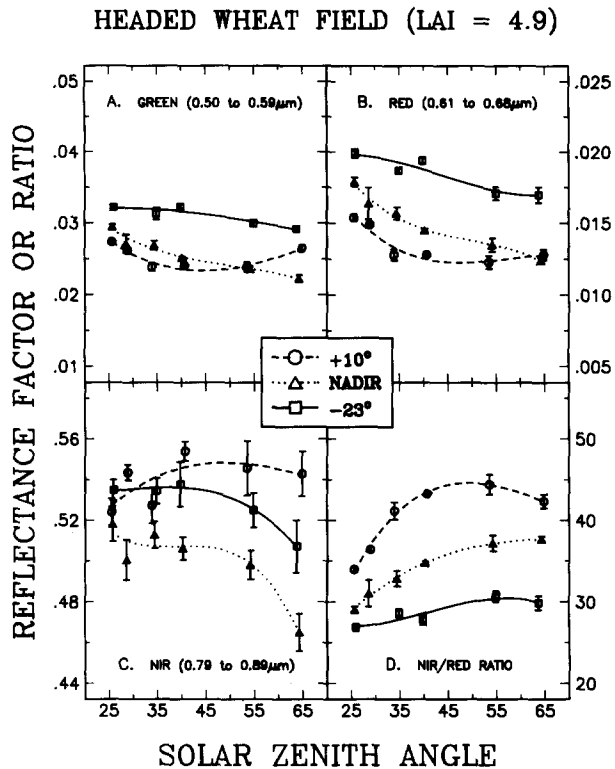

SOLAR ZENITH ANGLE

Figure 3. Ground-based, BRF in SPOT HRV wavebands and NIR to red ratios measured on 9 and 10 April 1989 in a well-watered wheat field having 100% canopy cover. Each data point is an average of 72 (off-nadir) or 144 (nadir) measurements. Vertical bars indicate a ±1 standard error from three 20-m-long transects in three adjacent borders. Lines represent best fit polynomial curves through data points for a given view angle.

view angle on sparsely vegetated surfaces. Results for one of the cotton fields (Site C of Table 1) are shown in Figures 2A)–C). The plants were about 2 months old, approximately 0.3 m tall, and covered about 21% of the soil when viewed from nadir. Row orientation was in a north–south direction. Reflectance in each wavelength interval varied considerably during the experiment, revealing some similarities with BRFs of a taller, denser cotton (*G. barbadense* L.) canopy (Kimes et al., 1984).

As was observed for the soil target, systematic changes in solar zenith and azimuth angles during the morning resulted in large changes in reflectances for a given view angle. In both visible wavebands, reflectance factors increased by a factor of 3 from early in the morning to midday when a maximum amount of soil was illuminated between the plants. In the NIR, values increased almost twofold from 0.23 to 0.40.

Because the cotton plants were small, overall scene reflectance was dominated by the relatively bright background soil, but reflectance was also affected by the amount of vegetation viewed by the radiometer. This is especially evident in Figure 2D) where the ratio of NIR to red reflectances clearly distinguish between the three cotton fields having slightly different, albeit small, green leaf area index values (LAI). These data reveal several features about the behavior of the visible and NIR light in partially vegetated targets. First, the effect of solar zenith angle on the NIR/red ratio increased as the amount of vegetation increased. It did not have an appreciable effect on the ratio from the furrowed soil [Fig. 1D)] or the cotton with the lowest LAI. However, in site C where plant biomass was the highest, we observed a 40% decrease in the ratio from morning to midday. Large solar zenith angles enhanced our ability to separate the different cotton fields using the ratio. Ratios observed when zenith angles were small tended to converge. This is an important consideration when attempting to separate cover classes in sparse vegetation or matching data collected via different sensor systems at different times of the day or locations.

The second feature was that these sparsely vegetated targets exhibited fundamentally different behavior than did the bare soil targets when viewed from an off-nadir direction. This is because the transmittance of light through plant tissues is wavelength-dependent. Shadows cast by plants in the visible portion of the spectrum are very "dark," as little visible light is transmitted through one leaf to the next or through to the soil surface. In the NIR, however, cotton leaves are relatively transparent; extinction of NIR light occurs only after light passes through six to eight layers of leaves (Thomas et al., 1967). Thus "shadows" in NIR are relatively bright and NIR reflectance retains its usefulness for detecting differences in biomass beyond the 100% canopy cover threshold possible with the naked eye. A radiometer pointed toward a canopy in the direction of the sun (the antisolar or "cold spot" is the positive view angle in this data set) will perceive a larger reduction in the visible wavelengths than in the NIR when compared with data collected at nadir. This causes an increase in the NIR/red. This phenomenon was pronounced in dense wheat canopies where soil was completely hidden from the view of the

radiometer (Pinter et al., 1987). This effect was also seen in NIR/red data collected in this study [Fig. 2D)]. The difference in the ratio between the nadir and +23° views increases for the canopies with larger plants. Ratios from nadir and −10° views were almost identical when examined for each of the cotton targets.

The Wheat Targets. Figures 3A)–D) show single band reflectance factors and NIR/red values for the well-watered wheat canopies (site D, Table 1) on 9 and 10 April 89. Our observations corroborate detailed bidirectional reflectance factors measured in the same wheat field on 10 April 1989 (Jackson et al., 1990, this issue). However, the data we show here embody natural canopy variation at spatial scales that are more comparable in size to satellite pixels because they represent an average of reflectance factors measured along 20 m transects that were spaced about 75 m apart in three adjacent irrigation borders. Data from the wheat targets were fundamentally different from the furrowed soil (Fig. 1) and partial cotton canopies (Fig. 2) for several reasons. First, the wheat canopy was dense (LAI = 4.9) and completely covered the soil. Most of the visible light incident upon the canopy was absorbed by the plants for potential use in photosynthetic pathways while a large amount of NIR light was reflected back to the radiometer by multiple layers of plant tissue. Thus reflectance factors in the green and red wavebands remained below 0.035 and 0.020, respectively, with the maximum values occurring at small zenith angles. NIR reflectance factors varied between 0.46 and 0.56, depending upon solar zenith and view angle.

The second reason for differences in bidirectional reflectance patterns pertains to features of wheat canopy architecture, most notably the presence of seed heads and awns. Extending 15–30 cm above the leaves on the measurement dates, they comprised the most conspicuous elements of the canopy when viewed from an oblique angle. Visual impressions that these structures were involved in forward scattering of light early in the morning were supported by increased reflectance factors in both the green and red wavebands at the +10° viewing angle [Figs. 3A) and B); solar zeniths > 50°]. At smaller zeniths, we observed that the pattern of visible light reflectance was similar to the partial cotton canopy, albeit at a much reduced level. The +10° view was darker and −23° view

was brighter than the nadir viewing direction depending upon the fraction of the field of view that was shadowed at the time of measurements. In contrast, off-nadir reflectances in the NIR always remained higher than those measured at nadir, presumably due to the unique scattering properties of the heads. We found slightly higher visible and slightly lower NIR reflectances for each of the transects in the dry wheat canopies (not shown), but the relative patterns for each view angle were almost identical to those of Figure 3.

Systematic changes in single waveband reflectance factors with viewing and illumination angles account for the large variation in NIR/red data for headed wheat canopies [Fig. 3D)]. Sensor viewing angle appears to be critical in determining the magnitude of the ratio (see also Fig. 4 in Jackson et al., 1990, this issue). At a solar zenith of 40° for example, the ratio in wheat declined by more than 35% (43–28 units) when view angle changed to −23° from +10°. For a partial cotton canopy (LAI = 0.52), a comparable 33° change in viewing angle only reduced the ratio by 10%. In wheat, the solar zenith had a relatively small effect on the ratio obtained when the radiometer was pointed at −23° but its influence increased greatly when the radiometer was at nadir and at positive viewing angles. At the +10° viewing angle, the ratio decreased abruptly from 43 to 33 with a 15° decrease in solar zenith angle. Such observations suggest caution, when multispectral vegetation indices such as the NIR/red ratio are used for assessing agronomic properties without advance knowledge of the bidirectional reflectance characteristics of each target.

Comparisons of Reflectance Factors at Overpass Time

The reflectance factors obtained from each of the sensor systems are shown in Table 3. Ground-based data were interpolated for overpass times of aircraft and satellite systems to minimize the effect that changing solar angles would have on comparisons of reflectance. The relatively large aircraft and satellite pixels in the wheat field were actually mixed composites of plant and soil because the wheat was growing in 27.5-m-wide irrigation borders separated by 2-m-wide berms of cultivated soil. To compensate for this difference and make data more comparable, ground data were adjusted

Table 3. Comparisons between Ground-, Aircraft-, and Satellite-Measured Reflectance Factors and the NIR/Red Ratio[a]

| | Nadir View Angles | | | | Off-Nadir View Angles | | | |
| | Ground | | Aircraft | | Ground | | Satellite | |
Target	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day
				Green (0.50–0.59 μm)				
Furrowed soil	0.099	0.097	0.095	0.096	0.080	0.110	0.107	0.152
Cotton	0.197	0.183	0.186	0.170	0.162	0.192	0.157	0.212
Cotton	0.149	0.132	0.150	0.132	0.114	0.145	0.128	0.177
Cotton	0.123	0.104	0.117	0.104	0.090	0.114	0.102	0.148
Dry wheat canopy	0.030	0.028	—	—	0.027	0.033	—	—
Adj. dry wheat field	0.035	0.034	0.041	0.040	0.031	0.039	0.065	0.095
Wet wheat canopy	0.028	0.027	—	—	0.026	0.031	—	—
Adj. wet wheat field	0.033	0.032	0.037	0.037	0.030	0.037	0.063	0.092
				Red (0.61–0.68 μm)				
Furrowed soil	0.149	0.147	0.150	0.152	0.122	0.165	0.142	0.202
Cotton	0.269	0.249	0.278	0.257	0.227	0.262	0.225	0.293
Cotton	0.182	0.170	0.207	0.185	0.148	0.190	0.168	0.226
Cotton	0.145	0.129	0.162	0.142	0.107	0.128	0.127	0.186
Dry wheat canopy	0.018	0.018	—	—	0.016	0.020	—	—
Adj. dry wheat field	0.028	0.027	0.040	0.039	0.024	0.031	0.065	0.090
Wet wheat canopy	0.016	0.016	—	—	0.014	0.019	—	—
Adj. wet wheat field	0.026	0.026	0.036	0.037	0.022	0.030	0.060	0.086
				NIR (0.79–0.89 μm)				
Furrowed soil	0.208	0.205	0.202	0.196	0.174	0.224	0.210	0.274
Cotton	0.401	0.382	0.388	0.364	0.350	0.394	0.328	0.412
Cotton	0.370	0.353	0.366	0.341	0.317	0.388	0.307	0.393
Cotton	0.365	0.347	0.354	0.331	0.297	0.345	0.286	0.380
Dry wheat canopy	0.517	0.516	—	—	0.538	0.536	—	—
Adj. dry wheat field	0.495	0.493	0.491	0.469	0.512	0.513	0.455	0.512
Wet wheat canopy	0.509	0.508	—	—	0.534	0.531	—	—
Adj. wet wheat field	0.487	0.486	0.488	0.466	0.508	0.509	0.454	0.509
				NIR / Red Ratio				
Furrowed soil	1.39	1.39	1.35	1.29	1.43	1.36	1.48	1.36
Cotton	1.49	1.53	1.40	1.42	1.54	1.50	1.46	1.41
Cotton	2.03	2.08	1.77	1.85	2.14	2.04	1.83	1.74
Cotton	2.52	2.69	2.18	2.33	2.78	2.70	2.25	2.04
Dry wheat canopy	28.72	28.67	—	—	33.62	26.80	—	—
Adj. dry wheat field	17.97	18.02	12.28	12.03	21.58	16.80	7.00	5.69
Wet wheat canopy	31.81	31.75	—	—	38.14	27.95	—	—
Adj. wet wheat field	18.97	19.04	13.56	12.59	23.24	17.17	7.57	5.92

[a]The targets identified as dry or wet wheat canopies represent plant reflectances only. The Adj. wheat field data were adjusted by a procedure explained in the text to represent a composite of plant canopy and soil berm between irrigation borders.

by combining reflectance factors from wheat and furrowed soil targets in an amount that was proportional to their occurrence (93% wheat, 7% soil). This adjustment had the effect of boosting wheat field reflectances in the visible region of the spectrum and decreasing them slightly in the NIR.

A principal reason for measuring nadir reflectance factors with both the ground and aircraft radiometers was to determine whether the intrinsic reflectance properties of the targets changed from one day to the next because of growth, water stress, surface soil moisture, etc. Nadir reflectance factors measured using both these systems were slightly lower on the second day for both years. However, the small change we observed can be explained by earlier acquisition times (as determined by the satellite overpass times) and hence larger solar zenith angles on those days. As expected, relatively large discrepancies were observed on consecutive days in both the off-nadir reflectance factors measured with the Exotech on the ground and those derived from the SPOT
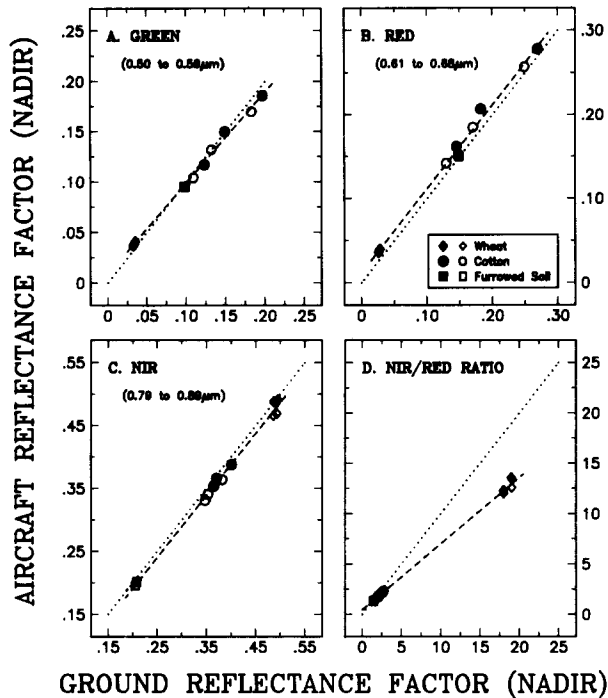
Figure 4. Comparisons between aircraft- and ground-based reflectance factors and NIR/red data in SPOT HRV wavebands during 1988 and 1989. Both data sets were collected with nadir-pointed radiometers having 15° FOV. The dotted line indicates a 1:1 correspondence. Symbol shape denotes target type. Filled symbols refer to data collected on Day 1 of each consecutive day experiment; open symbols, Day 2. The dashed line is a best fit least squares linear relation between all data points.

Figure 5. Comparisons between SPOT satellite- and aircraft-based reflectance factors and NIR/red data in HRV wavebands during 1988 and 1989. Aircraft data were collected with a nadir-pointed, 15° FOV radiometer while SPOT data were acquired with off-nadir sensors. SPOT data were corrected using optical depths measurements. The dotted line indicates a 1:1 correspondence. Symbol shape denotes target type. Filled symbols refer to data collected on Day 1 (positive HRV viewing angles) of each consecutive day experiment; open symbols, Day 2 (negative HRV viewing angles). Data for each day were fit separately with least squares polynomial functions (dashed lines).

HRV. The direction and magnitude of the changes were similar for both ground- and satellite-based measurements with the exception of the NIR reflectance of the wheat target where ground data changes from Day 1 to Day 2 were negligible but satellite data increased from 0.45 to 0.51.

Direct comparisons between aircraft and nadir ground reflectance factors and NIR/red data are shown in Figure 4. Dashed lines in this figure represent least squares linear regression between dependent and independent variables while the dotted line indicates 1:1 correspondence. In each wavelength interval, the coefficients of determination (R^2) were highly significant. The data indicated no bias related to day of observation and the standard error of the regression estimate for the dependent variable ($se_{y \cdot x}$) was small, averaging 0.006 across all three wavelengths. More importantly, the slopes of the regression lines were nearly 1, indicating excellent correspondence between air and ground measurements. The slight offset of reflectances in red and NIR may have
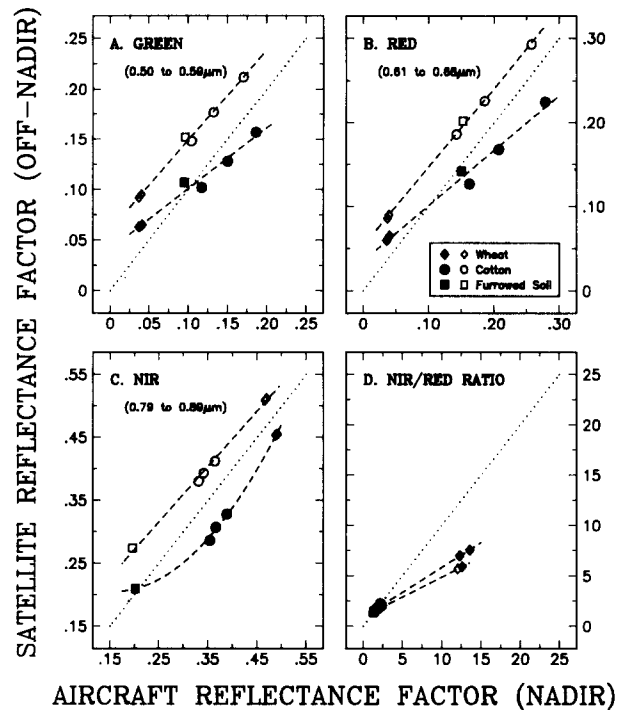
been caused by spatial variation between areas sampled by the two systems, small differences in technique or instrumentation, or the 150 m of intervening atmosphere that was not accounted for in the aircraft data. Relatively large differences between NIR/red data measured with the two systems were evident. This was not unexpected because this ratio is very sensitive to minor changes in the denominator. Small absolute differences in the estimate of red reflectances can be translated into large changes in the ratio.

Comparisons of atmospheric-corrected reflectance factors from SPOT with those obtained via the nadir looking radiometer on the aircraft are shown in Figure 5. Large differences in apparent reflectance occurred on each pair of days in both years, presumably due in part to the view angles of the satellite sensor which differed by 34° on the consecutive days. Interestingly, the data segre-

gated according to whether they were obtained at negative view angles (− 10.7° in 1988 and − 22.3° in 1989) or positive view angles (+ 23.4° in 1988 and + 11.7° in 1989) despite the fact that actual viewing angles differed by about 12° between the two years (Table 2) and one might expect four separate relations instead of two. Interpretation is further complicated by solar zenith angles which differed by 12–13° each year. The relationship between off-nadir satellite data and nadir aircraft data for the negative view angles was linear. The relationship for the positive viewing angles was also linear for the green and red bands, but not for the NIR. Relative BRF data obtained by Jackson et al. (1990, this issue) indicate only small changes in the BRF between 10° and 25° view angles (both positive and negative) at small solar zenith angles (their Fig. 2). The reason for the nonlinearity in the NIR shown in Figure 5 is not clear but it may be due to the partial canopy cover and relatively strong contribution from sunlit soil in the cotton fields. The data for positive and negative view angles straddle the 1:1 line, suggesting that, on days when SPOT employs a near nadir viewing angle, agreement between satellite and aircraft measurements would likely improve.

The reflectance factors derived from SPOT imagery are plotted versus interpolated, ground-based reflectances measured at corresponding viewing angles in Figure 6. Under ideal conditions (i.e., appropriate satellite calibration factors, exact atmospheric corrections and accurate ground-based, off-nadir reflectance factors) the data for the positive and negative look angles should coalesce into one line. It is obvious that this is not the case. Even though the predicted regression lines remain about 0.025 reflectance units apart, their separation is much less than that observed in the previous figure. When the data for both positive and negative view angles [Figs. 6A)–C)] were pooled, the average $se_{y \cdot x}$ was 0.019, a 50% improvement over similarly pooled data at dissimilar viewing angles (Fig. 5). This result suggests that at least half of the view angle effect in high resolution satellite data can be attributed to surface anisotropy, in contrast to the results of Pinker and Stowe (1990) for low resolution satellite data. The remaining deviation between view angles appears to affect both the visible and NIR in an equal manner, as the ratio of those bands seems to suggest [Fig. 6D)].
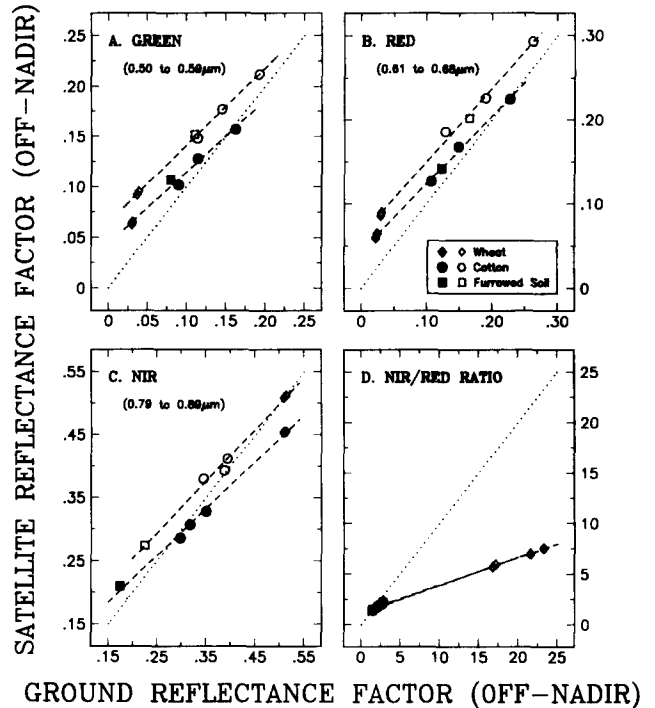

GROUND REFLECTANCE FACTOR (OFF–NADIR)

Figure 6. Comparisons between SPOT satellite- and ground-based reflectance factors and NIR/red data in HRV wavebands during 1988 and 1989. Both SPOT and ground data were collected using similar off-nadir viewing angles. SPOT data were corrected using optical depth measurements. Ground measurements utilized a 15° FOV radiometer. The dotted line indicates a 1:1 correspondence. Symbol shape denotes target type. Filled symbols refer to data collected on Day 1 (positive HRV viewing angles) of each consecutive day experiment; open symbols, Day 2 (negative HRV viewing angles). Data for each day were fit separately with least squares linear functions (dashed lines).

Data for both the negative and positive view angles in all three bands were linear. In each instance, the slopes of the regressions are less than 1 with satellite data, usually yielding higher reflectance values than ground values. The discrepancy is greatest for the lowest reflecting targets in each waveband. In fact, the visible reflectance factors in the wheat field were 2–3 times greater in SPOT HRV data than observed at ground level. Attributing the less-than-unity slopes to an atmospheric adjacency effect fails to resolve the consistent differences we observed between positive and negative view angles.

Further investigations will obviously be necessary to clarify this point but possible explanations for the discrepancy include: 1) inadequate characterization of inputs to the atmospheric correction algorithm, 2) inaccurate satellite sensor calibration, and 3) systematic error in off-nadir surface

reflectance measurements. By way of argument against the first explanation, the atmospheric correction procedure used for this analysis has provided consistent results for diverse atmospheric conditions during calibration of the Landsat TM and SPOT sensors at a high-reflectance gypsum sand site at White Sands Missile Range, New Mexico (Slater et al., 1986; Begni et al., 1986). It has also been applied to TM data acquired on six dates at MAC (over surfaces including mature cotton, wheat, alfalfa, and bare soil) with similar success (Holm et al., 1989). This is, however, the first application of the technique to oblique SPOT HRV data over very low-reflectance surfaces where small errors in path radiance can overwhelm the true surface signal. Atmospheric corrections for both the TM and the SPOT data were calculated using a radiative transfer code with the assumption that the surface reflectance was lambertian. Hart et al. (1990) examined this assumption using an approximate bidirectional reflectance distribution function for wheat in the radiative transfer code. Although approximate, their new correction factors reduced the difference between the positive and negative viewing angles that is shown in Figure 6. These results warrant further examination.

Concerning point 2) above, the SPOT-1 calibration coefficients used in the calculation of surface reflectance were the latest available (Moran et al., 1990, this issue) using in-flight calibrations of SPOT-1 at the White Sands site (Begni et al., 1986). To our knowledge, such calibrations have not been carried out over low reflecting surfaces. Nonlinearity in sensor response or presence of an intercept in the calibration curve could cause a deviation from ground measurements, but it is unlikely that such problems would cause consecutive day differences in apparent surface reflectance.

The off-nadir reflectance factors measured with ground-based radiometers at satellite overpass times were interpolated from plots of those data versus solar zenith angle. The low standard errors of the average reflectance values suggest that the interpolated values should be valid. Furthermore, the good correlation between nadir ground- and aircraft-based reflectances (Fig. 4) minimizes concern about spatial sampling errors in surface reflectance measurements. The field of view of the radiometers used on the ground and in the aircraft

was 15°, whereas the instantaneous FOV of the satellite sensor was considerably smaller. When viewing a nonlambertian surface, the difference in FOVs may introduce a bias that could partially explain differences in the view angle data.

CONCLUDING REMARKS

The effective application of remote sensing to agricultural resource management requires a thorough understanding of the dynamic bidirectional reflectance properties of important ground cover types, and knowledge of how that signal is propagated through the atmosphere to the sensor. Although this has always been true for satellites with nadir imaging capabilities, we believe the issue has become more critical as satellites with pointable sensor systems come into widespread use. Simultaneous experiments conducted at different altitudes are essential for confirming whether temporal variation in imagery is a direct result of 1) changing surface characteristics (i.e., plant growth or surface soil moisture), 2) unique BRF properties of the surface and changes in illumination/viewing geometry, or 3) variation in absorption, transmission, or scattering by the atmosphere.

In the present study, observations from nadir-pointed radiometers at ground and aircraft altitudes established that day-to-day changes in several typical agricultural surfaces were negligible. When these same targets were examined on consecutive days using SPOT satellite-based, off-nadir radiometers, differences in surface reflectances were pronounced. Reflectance factors from ground-based radiometers and comparable viewing angles revealed that approximately half of the variation in SPOT imagery was explained by unique BRF properties of the surface and changes in sensor viewing geometry.

The source of the residual differences between ground and satellite observations is unclear at this time. Our ground and aircraft radiometers represent a pragmatic compromise between the need to restrict the sensor's field of view and the requirement to sample a representative area. However, there is some question that comparisons between 15° FOV radiometers and the very narrow instantaneous field of view of the SPOT sensor may cause some of this uncertainty. Additional impor-

tant questions focus on incomplete parametrization of surface properties and their inclusion in radiative transfer codes. Such a conclusion implies difficulties in extracting quantitative agronomic information from isolated observations without *a priori* knowledge of the target.

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